SANDIA REPORT

Superconducting Gravity Gradiometers for Underground Target Recognition

Final Report

Mary Jayne Adriaans

Sandia National Laboratories

SF 2900Q(8-81)

Superconducting Gravity Gradiometers for Underground Target Recognition

Final Report

Mary Jayne Adriaans
Optics and Emerging Technologies Department
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-0980

ABSTRACT

One of the most formidable intelligence challenges existing in the non-proliferation community is the detection of buried targets. The physical parameter that all buried targets share, whether the target is buried armaments, a tunnel or a bunker, is mass. In the case of buried armaments, there is an excess mass (higher density) compared to the surrounding area; for a tunnel or bunker, the mass is missing. In either case, this difference in mass generates a distinct gravitational signature. The Superconducting Gravity Gradiometer project at Sandia worked toward developing an airborne device for the detection of these underground structures.

Intentionally Left Blank

BACKGROUND

One of the most formidable intelligence challenges existing in the non-proliferation community is the detection of buried targets. The physical parameter that all buried targets share, whether the target is buried armaments, a tunnel or a bunker, is mass. In the case of buried armaments, there is an excess mass (higher density) compared to the surrounding area; for a tunnel or bunker, the mass is missing. In either case, this difference in mass generates a distinct gravitational signature. The gravitational signature of a truck, a tank or a nuclear warhead is infinitesimal compared to the earth's gravity, but the development of a new field-deployable superconducting accelerometer, which is the goal of this project, would add gravity to the optical, radar, x-ray, thermal and other methods that can help verify arms control treaties or ferret out an enemy's armaments and underground structures.

The earth's internal churning creates a gravitational noise thousands of times as strong as the signals being sought. By combining two accelerometers in one instrument and canceling the common-mode noise that both detect, it is possible to create a gravity gradiometer that responds only to nearby variations in the gravitational field. Gradiometer research at the University of Maryland (UMD), under the direction of Professor Ho Jung Paik, has achieved noise levels in superconducting accelerometers as low as 0.02 E/$\sqrt{Hz}$, where 1 E = 1 Eotvos $\equiv 10^{-9}$ sec^{-2}. This exceptionally low noise level is about a factor of ten thousand times less than the intrinsic gravity noise created by the Earth. To put this unit in perspective, the radial gravitational force gradient at the surface of the earth is approximately 4,500 E even though it is often assumed to be zero (constant gravity g = 9.8 m/s^2) . The devices, currently under construction at UMD, lend themselves to conducting local gravity gradient surveys.

Local airborne surveys are required for studying gravity fields with spatial resolution better than 100 km, which is what would be required for locating underground targets of interest. With the use of GPS, rapid survey of large regions has become possible by using a gravimeter (measures a gravity signal as opposed to a gravity *gradient* signal) on a stabilized airborne platform. However, with the limits of GPS positioning, improvements beyond 1 mgal (10^{-3} gal = 10^{-3} cm/sec^2) at 5 km is unlikely. Since a gradiometer measures the gravity gradient, it is more sensitive to signals with small spatial extent. The gravitational acceleration *a(r)* created by an object of total mass *M* at a distance *r* from the point of observation is in the direction of the object and is given by:

$$a(r) = GM/r^2 \qquad (1)$$

where G = 6.7x10^{-11} m^2/kg s^2 is the universal gravitation constant. A gravimeter would measure *a(r)*. By taking the first derivative of *a(r)* with respect to r, we arrive at an expression for the gravitational acceleration gradient *Γ(r)*:

$$\Gamma(r) = 2GM/r^3. \qquad (2)$$

A gradiometer would measure *Γ(r)*. For example, a 70 kg person at a distance of 2 meters would produce a gravity gradient signal of about 1 E. Similarly, a 10^6 kg chamber (a sphere with a radius of approximately 4.7 m) at a distance of 50 meters would also produce a gravity gradient signal of about 1 E. With its relatively wide bandwidth of

about 1 Hz, a Superconducting Gravity Gradiometer (SGG) would allow rapid surveying of large areas with very high spatial resolution.

Modeling has shown that in order to recover gravity to 0.1 mgal with a spatial resolution of 100 m, a gradiometer on a typical airplane requires an input noise of 0.1 $E/\sqrt{Hz}$. The acceleration noise in an airplane is approximately 0.1 $m/s^2\sqrt{Hz}$, which requires a rejection of platform acceleration of about 10^{10}. Stabilizing a gradiometer against linear motion in an airplane is impossible because deviations of the airplane from its straight line flight path exceed the dimensions of its cabin. Consequently, linear accelerations must be rejected by the gradiometer itself. For the rotational degrees of freedom, stabilization is straightforward using gyro-stabilized platforms.

Angular accelerometers, one of the components in an SGG, can be designed to have a very high inherent rejection of linear acceleration. Two such angular accelerometers can then be combined to form an off-diagonal component gradiometer with extremely high linear acceleration immunity. The off-diagonal component SGG, with an intrinsic sensitivity of approximately 0.1 $E/\sqrt{Hz}$, is being constructed under contract with the University of Maryland.

SUPERCONDUCTING GRAVITY GRADIOMETER

Figure 1 shows a simple schematic of a superconducting accelerometer. The accelerometer is made up of a superconducting proof mass, m, attached to a platform via a weak spring, a superconducting sensing coil, and a SQUID (Superconducting Quantum Interference Device). A persistent current, I_o, is stored in the loop made up of the sensing coil and the SQUID input coil. When a gravity signal is applied to the proof mass, the superconducting mass is displaced relative to the sensing coil, changing the magnetic field inside the coil due to the Meissner effect. This changing field induces a change in the persistent current, I_o, which is then detected by the SQUID amplifier. The spring-mass system converts platform acceleration or a gravity signal into a displacement of the proof mass, the superconducting circuit converts this displacement into an electrical current in the SQUID input coil, and the SQUID converts this induced current into an output voltage signal.

Two types of gradiometers can be constructed from the simplified schematic shown in figure 1. These are the in-line and the cross-component gradiometers. The expression for the gravity gradient in equation (2) can also be expressed in Cartesian coordinates for a mass of arbitrary shape. The gravity field is given by a scalar potential, $\phi(x)$, which is not directly observable. The first derivative of the scalar potential gives a vector which is the gravitational acceleration: $g_i = -\partial\phi/\partial x_i$, where i corresponds to each of the spatial directions x, y, and z. The gravity gradient is the second spatial derivative
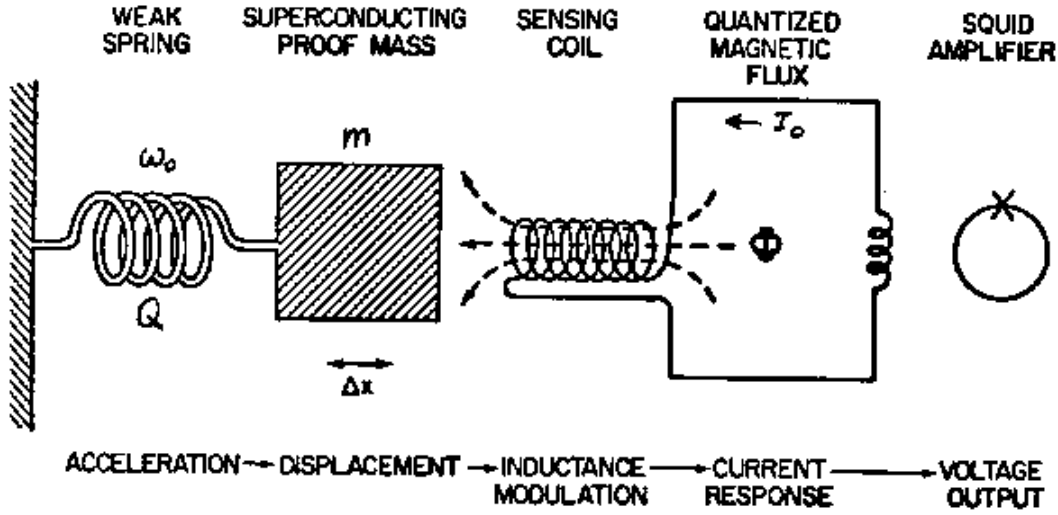
Figure 1: Schematic of a Superconducting Accelerometer

of the scalar potential (or the first derivative of the gravitational acceleration), and this quantity is a tensor:

$$\Gamma_{ij} = \partial^2\phi / \partial x_i \partial x_j. \tag{3}$$

This gravity gradient tensor is symmetric ($\Gamma_{ij} = \Gamma_{ji}$) and the trace of the tensor is given by an expression for the gravitational inverse-square law:

$$\sum \Gamma_{ii} = \nabla^2\phi = 4\pi G\rho, \tag{4}$$

where ρ is the mass density. In free space $\rho = 0$, so the trace of Γ must be equal to zero, $\sum \Gamma_{ii} = \Gamma_{xx} + \Gamma_{yy} + \Gamma_{zz} = 0$. Therefore, there are only five independent terms in the gravity gradient tensor: two diagonal components (in-line components) and three off diagonal components (cross components).

A gradiometer to measure the in-line components of the gravity gradient can be constructed by differencing the signals between two linear accelerometers. The linear accelerometers are aligned along their sensitive axes. Differencing the acceleration signals in the superconducting circuits between the two linear accelerometers gives Γ_{ii} and summing the signals gives the linear acceleration g_i. The cross-component elements of the gravity gradient tensor can be measured by differencing signals between two concentric angular accelerometers whose arms are perpendicular to one another. Differencing the acceleration signals in the superconducting circuits of the angular accelerometers gives Γ_{ij} and summing them gives the common-mode angular acceleration, α_k, of the system.
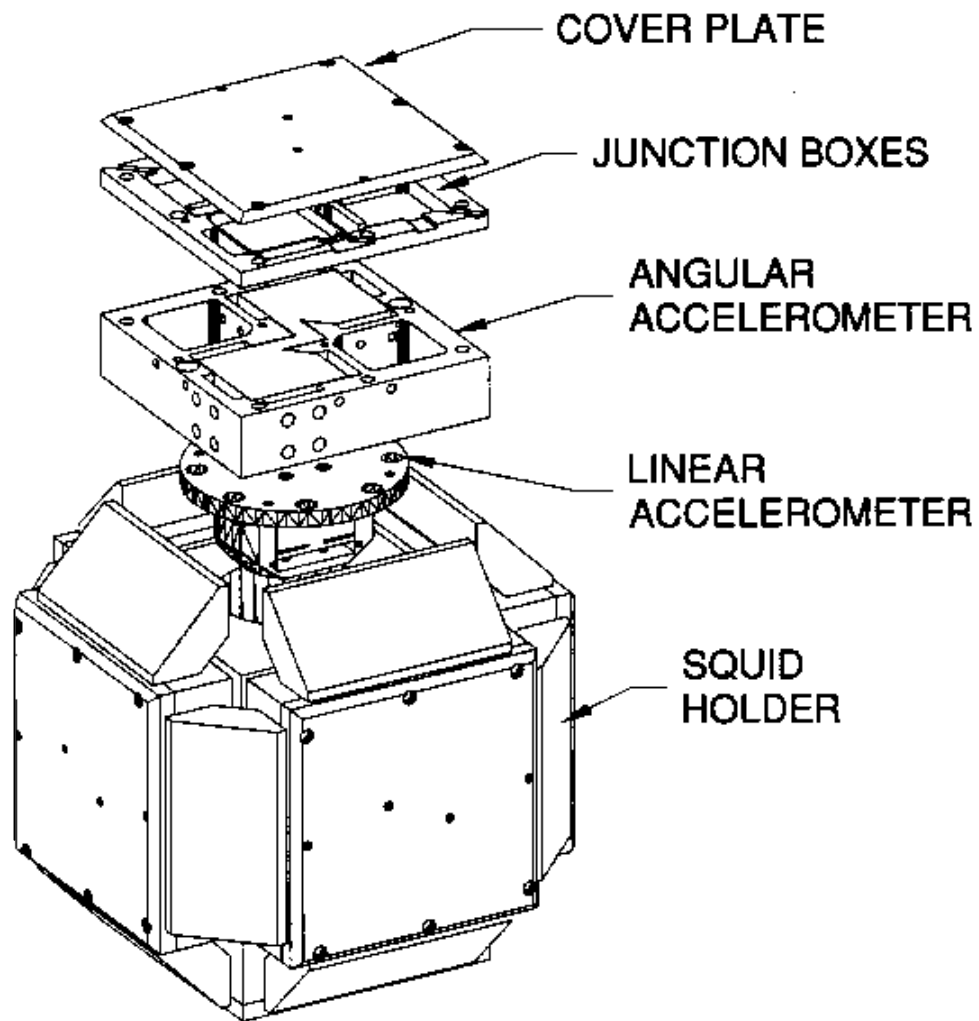
7

Figure 2: Exploded View of a Cross-Component SGG

The three-axis Sandia SGG, designed by the University of Maryland and shown in figure 2 (with half of one axis expanded to show detail), is being built for airborne

application. In an airborne application the linear acceleration rejection must be at least 10^{10} or higher due to the fact that the platform of the SGG cannot be stabilized against large translational motion experienced by aircraft, which can often exceed the dimensions of the cabin. The linear acceleration rejection can best be accomplished by taking advantage of a cross-component gradiometer. The cross-component device can be designed to be inherently insensitive to linear accelerations by constructing pivoted, rotating arms whose mass moments are balanced to high precision before assembly. Designing the pivot of the angular accelerometer in the cross-component device so that it is "stiff" against motion in two degrees of freedom, yet sensitive to motion for the desired rotational acceleration, will further limit unwanted signals from linear accelerations of the aircraft.

All of the parts identified in figure 2 are made from the superconducting material niobium. The central mounting cube is constructed from a titanium alloy. The angular accelerometer (figure 3), with its pivoting proof mass, is cut from a 4"x4"x1" solid block of niobium by wire electron discharge machining (EDM). However, the actual pivot itself is made from a titanium alloy pin that has been diffusion bonded into the niobium. Except for two central mounting cubes and one of the angular accelerometers, all parts for the SGG were manufactured at the University of Maryland.
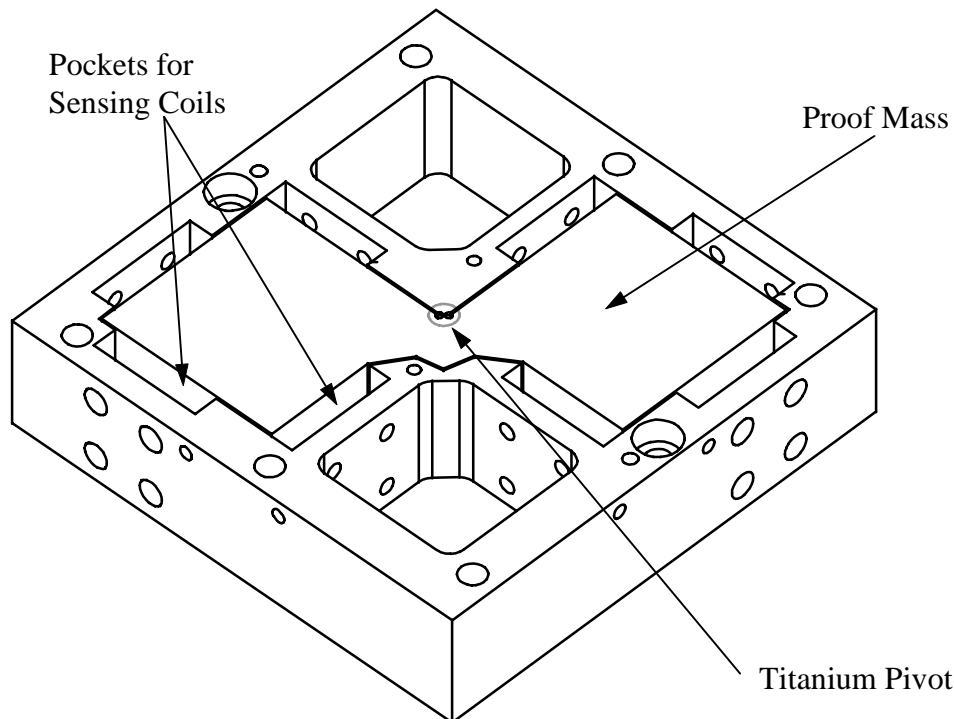

Figure 3: Angular Accelerometer

CHARACTERISTICS OF THE ANGULAR ACCELEROMETER

A structural analysis of the angular accelerometer was completed using the Algor finite element analysis package at UMD, and COSMOS at SNL. The stress distributions in the angular accelerometer under static acceleration loads were computed. From these calculations, it was concluded that the most serious stress concentrations were those caused by the bending of the pivot. One concern was that unless the stress was kept approximately a factor of three below the standard (0.2%) yield stress, microyielding in the pivot could affect performance. Therefore, for the stress in the pivot to be kept below this level, the pivot could not be niobium unless the gaps between the proof mass and the stops were made unacceptably small. This led to the current composite design with a diffusion bonded titanium alloy pivot.

A modal analysis of the angular accelerometer was also performed using finite element techniques. The frequencies and shapes of the modes below 3 kHz were computed. The results confirmed a UMD derived analytic expression for the pivot spring constant and showed that the only mode with a frequency of less than 1 kHz is a 300 Hz mode for twisting about the y-axis (along the plane of symmetry). To first order, the sensing circuit does not couple to this mode.

The design of the angular accelerometer was tuned to achieve isotropic response to acceleration-induced errors. A critical parameter of the angular accelerometer is the mass offset, the distance between the center of mass of the proof mass and the center of bending of the pivot. This mass offset determines the inherent rejection of linear acceleration. A potential problem for a cross component gradiometer operating in the presence of the large linear accelerations experienced on a survey aircraft is an offset induced by acceleration. After careful consideration of this error source, it has been shown that the error can be canceled to the degree the induced mass offset is isotropic in the plane perpendicular to the pivot or z-axis. Using finite element analysis, it was determined that the offset induced by acceleration along the y-axis (along the plane of symmetry) is caused primarily by distortion of the proof mass, whereas the offset induced by acceleration along the x-axis is caused primarily by distortion of the pivot. By iteratively adjusting the proof mass and pivot shape and recalculating the induced offsets, the offsets for the two acceleration components were matched to within a few percent, sufficient to remove this as a major error source.

Fabrication of the majority of the parts, including two of the three angular accelerometers that have been built, has occurred at the University of Maryland. After initial fabrication of the parts by the Physics Department's state-of-the-art wire EDM facility, which required cutting intricate shapes to very tight tolerances, multiple heat treatment steps were required in a high vacuum furnace. These heat treatments relieve the stress on the components caused by machining.

In order to achieve the balanced proof mass necessary for the high inherent rejection of linear acceleration in the angular accelerometer, UMD has developed techniques for measuring and correcting the mass offset. To measure the mass misbalance, one of the sensing coils is replaced by a capacitor plate and the accelerometer

is placed in a vacuum can on a table which can be tilted with an electromagnetic shaker. The displacement of the proof mass is measured with a capacitance bridge while the table is sinusoidally rocked at low frequency. By synchronously detecting the proof mass displacement and the table tilt, and measuring the response as a function of frequency with the proof mass in three orthogonal orientations, the mass offset can be determined. The total error in the measurement of offset is less than 0.1 µm (1 σ). A method for using wire EDM to trim the mass balance was developed, and the ability to adjust the mass offset to approximately 0.1 µm was demonstrated. UMD also developed a series of low temperature tests for the angular accelerometers. After mass balancing, the angular accelerometers were mounted on the UMD in-line component gravity gradiometer and tested at low temperature. Techniques for measuring the mass offset at low temperature, and software that allows for compensation of these errors using signals from the linear accelerometers on the SGG, were developed.

After fabrication, the center of mass offset of the three angular accelerometers was measured. The procedure was similar to that described in the previous section, except that several improvements were made. A new bridge circuit was built that used two capacitor plates and a ratio transformer to provide better signal stability and better balancing of the electrostatic forces on the proof mass. The previous data acquisition system was replaced by a VXI-based system that is programmable with LabVIEW. A LabVIEW program was developed that automated much of the very lengthy procedure. Measurements on the angular accelerometer produced at SNL and the two produced so far at UMD indicate that the center of mass offset is approximately 7 µm for the SNL accelerometer and 3 µm for the two UMD accelerometers. All of these offsets are correctable, but the resonance frequency of the SNL accelerometer was 5.5 Hz, while those of the two UMD accelerometers were at the design value, 7.1 Hz. Since matching of the resonance frequency is desirable between pairs of angular accelerometers, only the two UMD accelerometers were balanced. The mass trimming of one accelerometer has been completed, and its measured mass offset is less than 0.1 µm. This is approximately the limit of mass trimming resolution expected using the wire EDM, which removes mass from the entire height of the proof mass.

WORK TOWARDS AN AIRBORNE SGG

The key to detecting underground structures with the superconducting gravity gradiometer, described above, is to get the device airborne or, at the very least, on a movable platform. Work towards achieving an airborne SGG has included designing an airborne cryostat, measurements of vibrational noise on several different aircraft,

SCHEMATIC OF AIRBORNE GRADIOMETER SYSTEM

Dewar outer shell

Liquid helium in foam

SGG

Support strut (1 of 6)

3-axis stabilized platform (Contraves spherical bearing type)

Vibration isolator
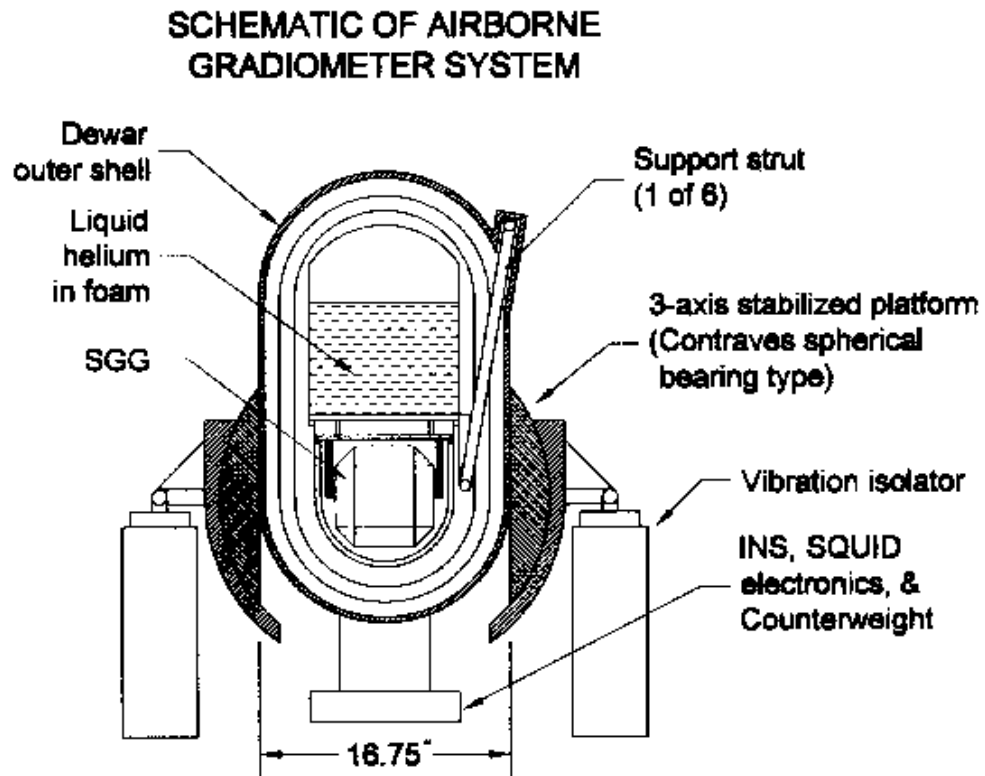
INS, SQUID electronics, & Counterweight

16.75"

Figure 4: Design for Airborne SGG System

simulations of gravity signals from potential targets and some investigations into the effects of terrain.

A potential design for the airborne cryostat for the SGG is shown in figure 4. The compact three-axis cross-component SGG, that is pictured in figure 2, fits in an 8.25" diameter sphere and weighs approximately 20 kg. The SGG will be placed inside a compact low boil off cryostat which would have a liquid helium hold time of greater than 48 hours. In order to prevent gravity signals from sloshing liquid helium, the cryostat can be filled with foam to restrain the helium motion. The cryostat itself, which is roughly 18" in diameter, 3' tall and weighs less than 50 kg, can be mounted on a gyro-stabilized platform which should provide passive vibration isolation above 1 Hz, and three axis attitude stabilization.

The expected performance of an airborne SGG system has been calculated and modeled. The intrinsic noise of the Sandia SGG is expected to be 0.02 E/√Hz over a bandwidth of 0.03 Hz to approximately 1 Hz, with a 1/f noise below 0.03 Hz. This is an improvement by a factor of 500 in sensitivity and a factor of 50 in spatial resolution over the Bell gradiometer. The Bell gradiometer (or the Gravity Gradiometer Survey System, GGSS, of Bell Aerospace) is an instrument which has achieved a resolution of about 12 E at a 10 km wavelength. Figure 5 shows the noise performance of a standard gravimeter and the Bell gradiometer compared to the expected performance of an airborne SGG.

The acceleration noise of three aircraft, a Fuji blimp, a Twin Otter, and a P3 Orion, were measured by investigators at the University of Maryland. Six Sundstrand accelerometers were fixed to a stiff aluminum mounting plate and placed in each aircraft. It was found that the Twin Otter had the most acceptable acceleration environment and will probably be the first choice of aircraft for testing once an airborne SGG has been assembled. The expected performance of the SGG system should overcome this aircraft motion. The linear acceleration rejection is predicted to be approximately 10^{10} after compensation by the instrument. A rejection factor of 10^6 comes from the mass balance of the superconducting accelerometer and the remaining factor is measured and rejected. The angular acceleration rejection is expected to be 10^7 after compensation, and approximately 10^9 after placement on a gyro-stabilized platform. Once the SGG is placed on an aircraft, its sensitivity should be approximately 0.1 E/√Hz over a bandwidth of 0.01 to 1 Hz with a 1/f noise below 0.01 Hz. This sensitivity would correspond to the detection of a 15 meter cube bunker at a distance of 130 meters with a signal to noise ratio of approximately 10.

Figures 6 and 7 show simulated results for airborne gradiometer scans over a bunker and over a tunnel. The terrain in these simulations was relatively smooth with only small variations over length scales of more than 100 m. In most areas on the Earth, terrain features do change slowly over length scales greater than 100 m. Since the SGG has a resolution of better than 100 m, it will be able to distinguish small objects from such a background. With the use positioning instruments, terrain irregularity can be

AIRBORNE GRAVITY SURVEY
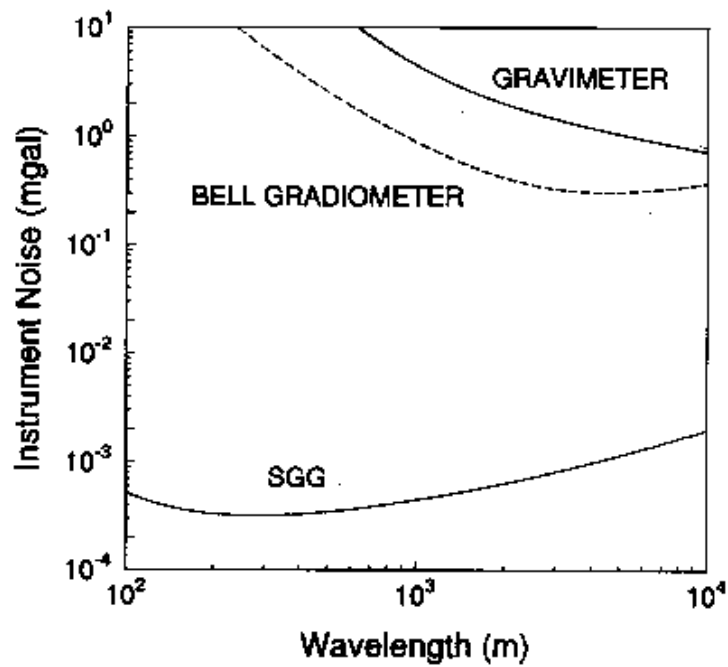
AIRCRAFT

Altitude:	100 m
Speed:	100 knots

INSTRUMENT NOISE

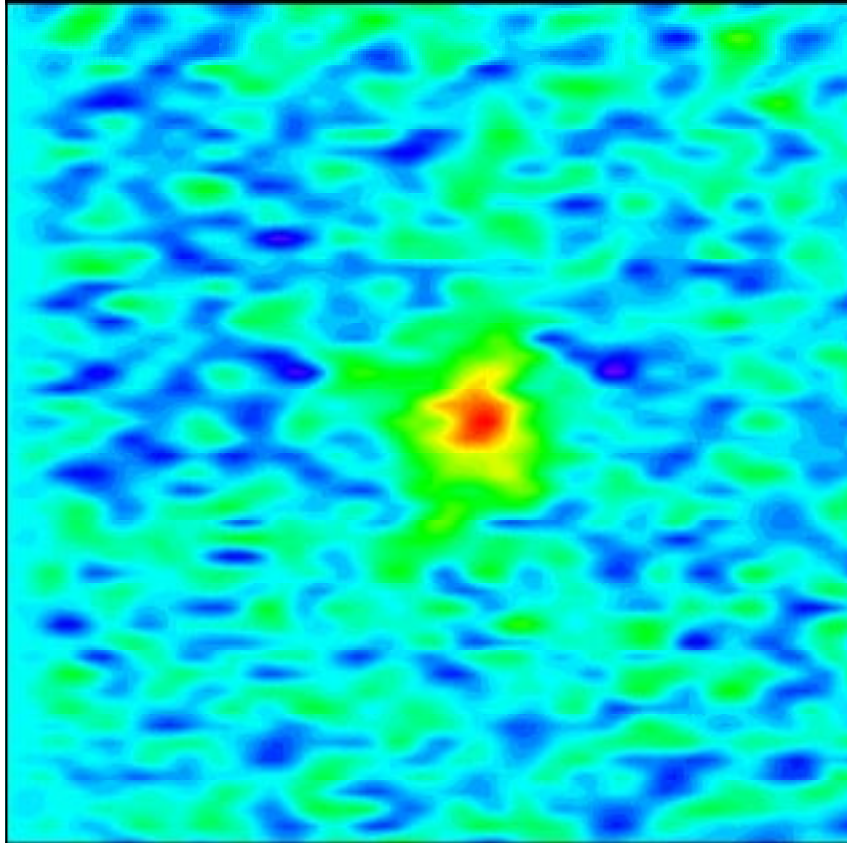|	
Gravimeter:	J.M. Brozena and M.F. Peters, Geophysics 53, 245 (1988), and Carson Geophysics web page
Bell Gradiometer:	C. Jekeli, Geophysics 58, 508 (1993)
SGG Noise:	$0.1 \text{ E Hz}^{-1/2}\left[1+\dfrac{0.01 \text{ Hz}}{f}\right]^{1/2}$

Figure 5: Estimated Performance of the Airborne SGG

GRAVITY GRADIENT SIGNAL FOR BUNKER

(Area shown: 1 km x 1 km)

$\rightarrow$ DIRECTION OF FLIGHT (20 s)

BUNKER
   SIZE: 15 m   x 15 m   x 15 m
   DEPTH: 30 m

SIGNAL
   NOISE: 0.1 E Hz$^{-1/2}$
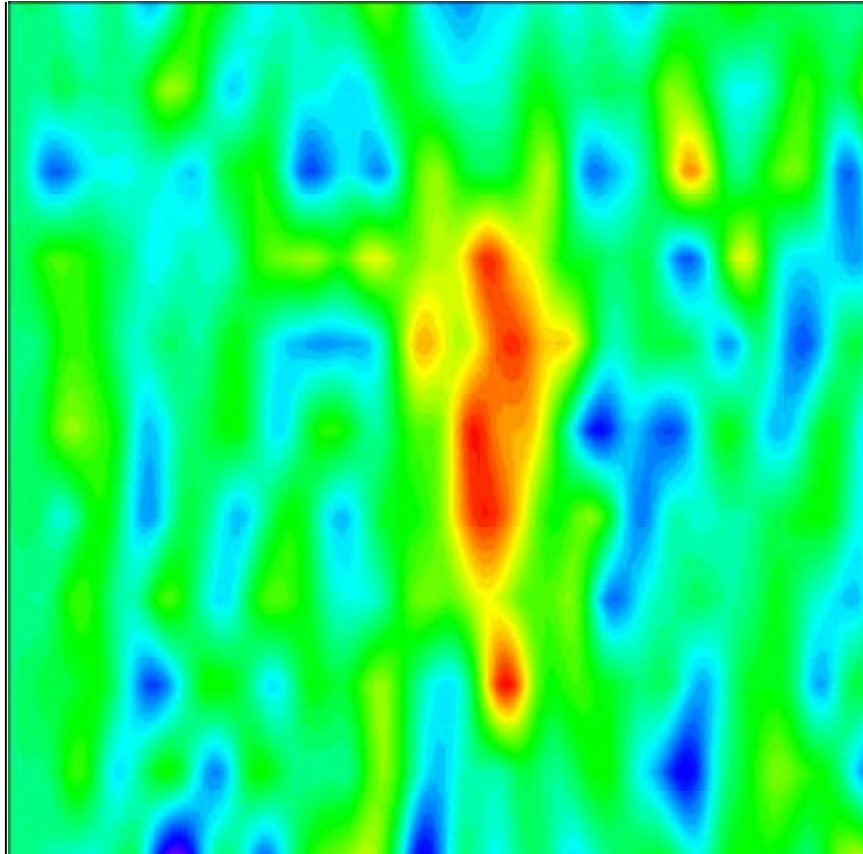   BANDWIDTH: 0.5 Hz

AIRTCRAFT
   ALTITUDE: 100 m
   VELOCITY: 100 knots

Figure 6: Estimated Performance of the Airborne SGG: Bunker

GRAVITY GRADIENT SIGNAL FOR TUNNEL
(1 km x 1 km)

→ DIRECTION OF FLIGHT (20 s)

TUNNEL
   SIZE: 3.0 m x 3.0 m x 500 m
   DEPTH: 30 m

SIGNAL
   NOISE: 0.1 E Hz$^{-1/2}$
   BANDWIDTH: 0.5 Hz

AIRTCRAFT
   ALTITUDE: 100 m
   VELOCITY: 100 knots

Figure 7: Estimated Performance of the Airborne SGG: Tunnel

measured and the gravity signals can be computed and subtracted to the extent that the mass density can be modeled. The uncertainty in the density of the surrounding terrain is the ultimate limit to the detection of hidden targets. However the gravity of such an area can be surveyed repeatedly and monitored for any changes.

SUMMARY

The use of the Superconducting Gravity Gradiometer offers a unique solution for the detection of underground targets. Some of the performance advantages of the SGG arise from the fact that the SGG is a cryogenic instrument. At low temperatures mechanical friction and electrical resistivity are very low, which allow for a very low noise device. Operating near liquid helium temperatures also provides for very low amplifier noise with the use of the SQUIDs. Also at low temperatures, the thermal expansion coefficients of materials are reduced by three or four orders of magnitude and provide for extremely high mechanical stability. The overall stability of the device therefore provides for a good dynamic range so that acceleration signals can be differenced before amplification, allowing the platform acceleration signal to be reduced by approximately four orders of magnitude.

The original objective proposed in the plan for the Superconducting Gravity Gradiometer LDRD was to complete a full field demonstration of a three-axis SGG on a remotely operated mobile platform. However, moving from a three-axis laboratory system to a full field deployable system introduced a number of unanticipated technical difficulties. It was determined early in the project that the accelerometers which were adequate for laboratory work would not be sufficient for field work, therefore a great deal of redesign work was completed (see the section on angular accelerometers). Resources were expended before the final objective could be met. At the time of the writing of this report, all parts necessary for a laboratory test of a one-axis system have been completed and are being assembled. In order to complete the original objectives of the program additional funding and work are necessary. The work remaining can be divided into three main categories: manufacturing, detailed design of the mobile cryostat and platform, and integration and field testing. Since all the modeling and design work for a complete three axis SGG has been accomplished, all that remains to complete a three axis system is the machining and assembly of components for the two remaining axes (which are identical to the single axis system already completed). Once the three axis SGG is assembled a full laboratory test must be completed. Next, a detailed design of the cryostat and mobile mounting platform must be finalized and the system built. Once this is completed, the SGG can be integrated into the platform and then tested in a field environment.

REFERENCES

H. A. Chan, M. V. Moody, and H. J. Paik, Phys. Rev. D **35**, 3572 (1987).
H. A. Chan and H. J. Paik, Phys. Rev. D **35**, 3551 (1987).

DISTRIBUTION: